

## **THE IMPACT OF SEA ICE ON THE PERIODIC SHALLOW WATER DYNAMICS IN THE LAPTEV SEA (SIBERIAN ARCTIC)**

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### **ABSTRACT**

The impact of sea ice on the periodic currents in the eastern Laptev Sea was evaluated in 1998–1999 within the framework of the Russian-German project “Laptev Sea System 2000”. Acoustic Doppler current profiler (ADCP) records from two moorings deployed for one year were analyzed. Ice conditions, as derived from remote sensing and ADCP data, were shown to significantly affect surface circulation down into the pycnocline layer. With fall freeze-up, the tidal currents shift from a barotropic to a baroclinic regime and are furthermore amplified in the pycnocline. Opening of polynyas induces a return to the initial barotropic mode with surface water dynamics primarily controlled by atmospheric forcing.

### **INTRODUCTION**

The sea-ice cover strongly affects the Arctic continental shelf environment. However, comparatively little is known about the influence of different ice conditions upon shallow water dynamics in a water column that is highly stratified due to input of riverine freshwater in the summer months. This is particularly true for the broad Siberian shelves, which have received little attention in comparison with work carried out from drifting stations over the deeper Arctic Ocean. To improve the lack of longer-term current profiling records in the Siberian Arctic, two moorings equipped with upward looking acoustic Doppler current profilers (ADCP, profiling depths of 40 and 22 m) were deployed in the eastern Laptev Sea for a one-year period within the framework of the Russian-German project “Laptev Sea System 2000”. The study region is strongly impacted by Lena River runoff. Ice conditions vary from open water in summer to completely ice-covered in winter. Between March and May, the Great Siberian coastal polynya (Zakharov, 1997) opens up episodically along the margin of the landfast ice. This paper discusses the impact of the sea-ice cover on the periodic

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currents in the eastern Laptev Sea and other Siberian shelf regions that have not been considered in any detail from this perspective.

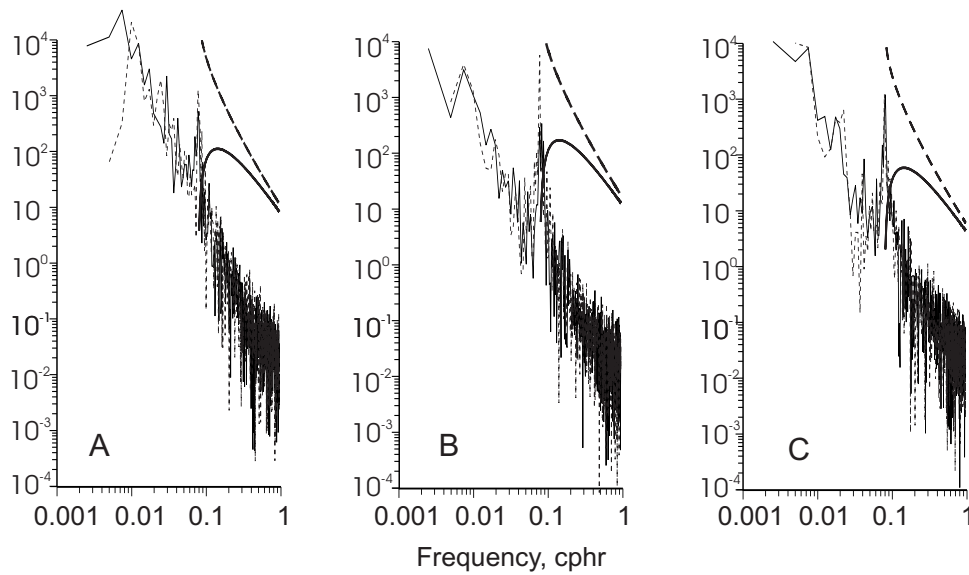


Figure 1: Horizontal velocity (thin curves) and Garrett-Munk (bold curves) spectra at the pycnocline level for anticlockwise (dashed curves) and clockwise (solid curves) components at station YANA. A – ice free conditions (August 8 to 29, 1998, 12 m depth); B – under landfast ice (December 18, 1998 to January 2, 1999, 16 m); C – polynya (April 26 to May 12, 1999, 16 m).

## DATA SET

Two moorings equipped with Workhorse Sentinel 300 kHz ADCP from RD Instruments were deployed from August 1998 till August 1999 in the eastern Laptev Sea (Fig. 3a). Station YANA was located in the eastern relic submarine valley of the Lena River at a depth of 44 m. Station LENA was deployed in shallower water to the northeast of the Lena Delta at 24 m waterdepth. Data were acquired every 2 m (YANA) and 1.5 m (LENA) depth, with 30 minute ensemble time interval and 30 pings per ensemble. For each samples, a total 21 (YANA) and 17 (LENA) depth bins were stored. Oscillations in sea level were recorded by a bottom-mounted CTD. The water column stratification was determined from CTD surveys completed at the time of deployment and recovery and during a helicopter survey in April and May 1999. Radarsat ScanSAR synthetic aperture radar (SAR) satellite images were obtained twice a month through the Alaska SAR Facility, augmented by daily passive microwave scenes (Special Scanner Microwave/Imager, SSM/I, 85 GHz channel) to determine the progression of freeze-up in 1998 evaluate ice conditions in the vicinity of the mooring sites. The backscatter signal strength of the acoustic Doppler echo also provided information about ice conditions above the mooring.

## RESULTS

The spectra of currents obtained under different ice conditions (Fig. 1) are lower than the canonical Garrett-Munk (GM) spectrum, as well as, in most cases, spectra obtained in other high-latitude ocean areas covered with ice (Levine et al., 1987; Plueddemann, 1992; Levine et al., 1997). This is mostly a result of the high density stratification due to substantial river runoff. The energy associated with the semidiurnal frequency band is comparable to the highest-energy regions of the Arctic Ocean (Plueddemann, 1992) and

exhibits seasonal variations. The magnitude of this maximum is roughly comparable for both open water conditions and in the polynya (Fig. 1 a and c). The highest values are associated with periodic under-ice currents during the fast-ice period (Fig. 1 b).

Wavelet analysis (Torrence and Compo, 1998) was employed to study seasonal variations in the semidiurnal wave spectrum. The wavelet transform was carried out with a non-orthogonal, Mexican Hat transform. For a 30-day window centered on the reference date, tidal analyses were completed for each depth bin and day of deployment using a simultaneous least-squares fit to the principal tidal constituents (Foreman, 1978).

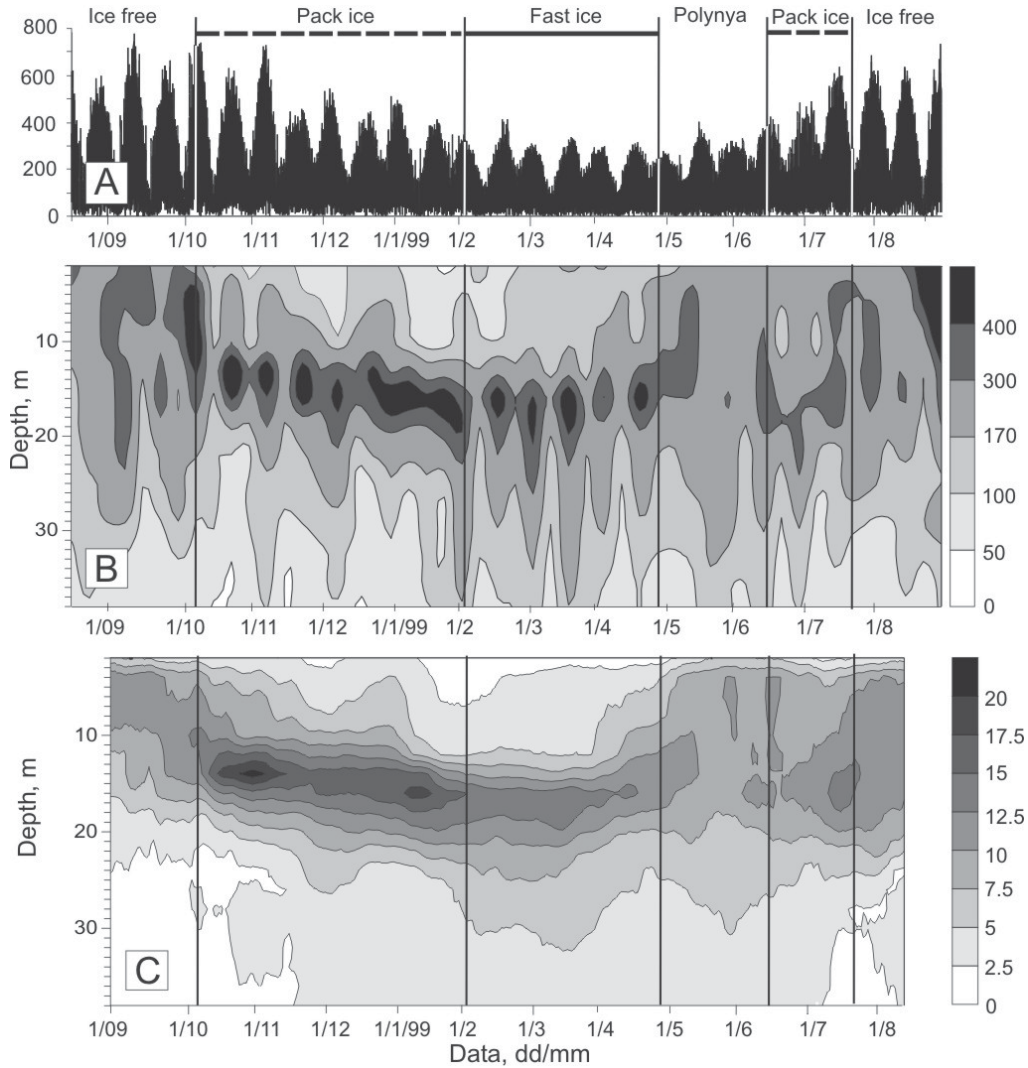


Figure 2: Wavelet transform of both sea level (A) and the north-south current component (NSCC) oscillations for semidiurnal (12.4 h) band (B) and amplitudes (cm/s) of lunar semidiurnal tidal ( $M_2$ ) currents (C) for station YANA.

Comparing the different panels in Fig. 2, we can confirm the tidal origin of the semidiurnal internal waves. The maxima of the sea level variation amplitudes coincide well with those in the north-south current components (NSCC). The dominance of the tidal signal also follows from the coincident depth distribution apparent in panels 2b and 2c.

A reduction in the magnitude of sea level oscillations under the ice (Fig. 2a) should be accompanied by a reduction in the barotropic tidal currents, as these are generated by astronomical forces and are typically uniform with depth. Nevertheless, a sharp increase in the semidiurnal tidal currents was observed in the winter pycnocline layer (Fig. 2c). The semidiurnal frequency band may also include freely propagating baroclinic internal tidal waves with a critical latitude of  $75^{\circ} 2.8' \text{N}$ , immediately north of station YANA. Hence, it appears that the current records also contain a baroclinic response to the interaction between the barotropic tide, stratification, bottom topography and the presence of an ice cover. During summer the energy of the semidiurnal tide is distributed evenly with depth, with the exception of a local maximum at the pycnocline level. In early October 1998, a rapid transformation of internal tidal waves was observed, accompanied by a reduction of the associated energy at all depth levels except for the pycnocline layer (Fig. 2b). For station YANA, considerable increase in tidal current amplitudes of the dominant constituent  $M_2$  occurred at the depth of the density interface (Fig. 2c).

In order to assess linkages between periodic currents and the ice regime, the wavelet transforms of the current records (Fig. 2b) and the results of the harmonic tidal analysis (Fig. 2c) were compared with remote-sensing (SSM/I and Radarsat ScanSAR, Fig. 3) and ADCP backscatter data. Both mooring sites exhibited the same general patterns. Onset of freeze-up occurred on October 4 and 5 for the LENA and YANA moorings, respectively (Fig. 3a). These dates coincide exactly with the transformation in tidal internal wave regularities (Fig. 2). Once a landfast ice cover was established at station LENA (December 2, 1998), internal tidal waves were further diminished in the surface layer and increased at the level of the pycnocline. At the YANA mooring, onset of the fast-ice regime results in a weak reduction of the tidal current amplitudes. From March 24 onwards, a coastal polynya began to open up in the eastern Laptev Sea from the fast ice edge in a northerly direction due to strong offshore winds. This flaw polynya extended over the YANA mooring between April 5 and May 5, 1999 (Fig. 3b,c). ADCP backscatter data indicate the presence of a polynya directly over the mooring at this site between April 26 and June 15, 1999. With the opening of the polynya the internal tidal wave spectrum is transformed into the “open water” regime. The wave energy is distributed fairly uniformly throughout all depth levels (Fig. 2b,c). From the middle of June 1999 onwards, during the period of landfast ice decay, the internal wave spectrum differs little from the “pack ice” regime in late 1998, up until the point of complete fast ice melt. The open water periods of 1998 and 1999 do not differ substantially. Thus, the amplification of baroclinic semidiurnal tidal internal waves is limited essentially to the winter period during the presence of an ice cover, regardless of ice type (thin new ice, drifting pack or landfast ice).

## DISCUSSION

The results obtained from this study differ principally from current understanding of the impact of an ice cover on internal wave dynamics. Typically, friction at the ice bottom surface and the reduced transfer of momentum through wind stress are referred to as the major factors resulting in a decrease of internal wave energy under an ice cover (Levine et al., 1985). In our case, the friction increase in the surface boundary layer enhanced by the ice cover does not simulate kvazi-amplification of internal waves. The amplification has been already observed at the initial freezing stages directly after freeze-up onset when the thin young ice does not contribute considerably to the boundary layer mixing.



Most likely, an amplification of the barotropic tide through interaction with the bottom topography and the stratification results in the formation of baroclinic internal waves.

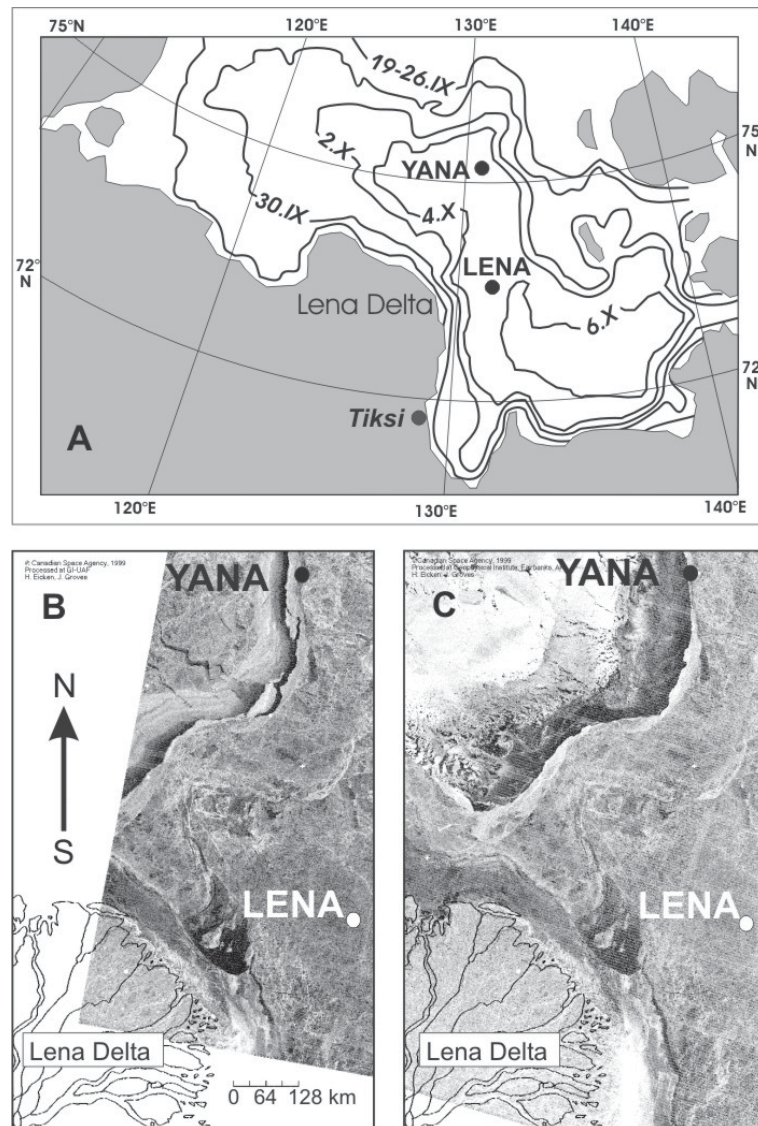


Figure 3: Freeze-up progression in the Laptev Sea in October 1998 according to daily SSM/I data (A) and the polynya evolution from April 5 (B) to May 5, 1999 (C) from Radarsat ScanSAR images.

Under open water conditions, and in contrast with the ice-covered case, the direct interaction of tidal baroclinic internal waves with the atmosphere can help dissipate internal wave energy into the higher-frequency bands. This may also explain why the observation of distinct baroclinic internal waves was limited to the ice-covered period. In order to evaluate this hypothesis, the wavelet transform of NSCC was calculated for high-band periodicity (periods of 4–8 h). Within this band, the energy of internal waves under the ice is appreciably lower in comparison with open-water and polynya conditions (Fig. 4). Similar results were obtained for the low-frequency band. It appears that nonlinear interaction between  $M_2$  and  $S_2$  tidal constituents intensifies fortnightly (MSF) oscillations and the corresponding downward energy flux during periods of open water. The ice-cover onset results in a reduction of the MSF tide constituent due to

differences in interaction between principal tidal constituents  $M_2$  and  $S_2$  underneath the ice. The interaction of near-inertial internal waves with subinertial wind-forced currents could be another possible reason for the propagation of energy towards lower frequency bands (Merrifield and Pinkel, 1996).

## CONCLUSIONS

A first long-term data set of currents under a variable sea-ice cover has been obtained for a full year over the Laptev Sea shelf, revealing strong seasonal variations in the current spectra. Similarities between the current and sea-level wavelet transforms as well as results of tide calculations allowed us to investigate the potential tidal origin of currents. The transformation of near-barotropic tidal currents into the baroclinic regime is associated with the onset of fall freeze-up. With the opening of a polynya, the initial barotropic conditions return. During most of the winter in the presence of an ice cover, lunar semidiurnal internal tidal currents are amplified from below 7 to as high as 20 cm/s. It seems that the interaction of barotropic tides with the density stratification and bottom topography generate the background baroclinic tidal internal waves. While their energy appears to be dissipated to higher frequency bands as a result of sea-atmosphere interaction under open-water conditions during summer, the details of this process are not clear.

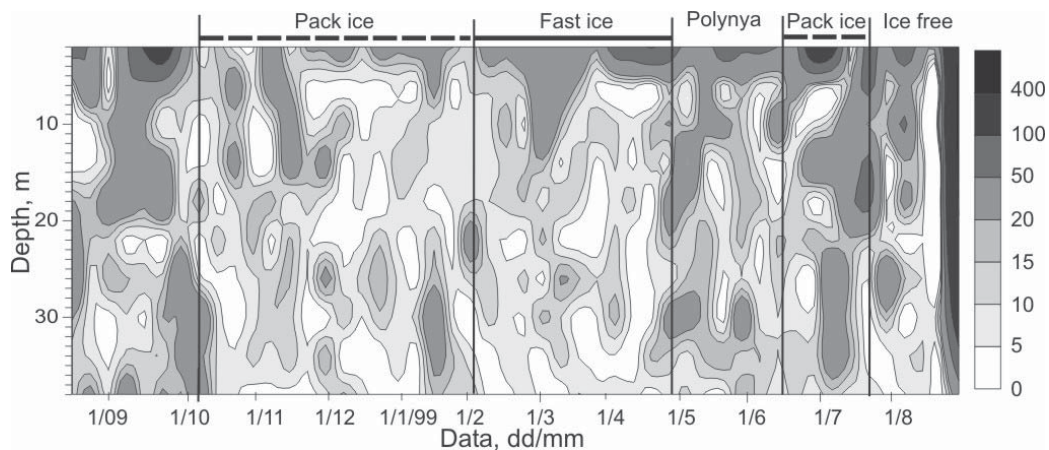


Figure 4: The wavelet transform of NSCC at a period of 4–8 h (YANA).

## ACKNOWLEDGMENT

This research was funded by the fellowship program of the Russian-German Otto Schmidt Laboratory for Polar and Marine Research. Additional support from the National Science Foundation (OPP-9876843) and Frontier Research System for Global Change are gratefully acknowledged. SAR data were obtained through a NASA-ADRO grant and provided by the Alaska SAR Facility.

## REFERENCES

- Foreman, M.G.G. *Manual for Tidal Currents Analysis and Prediction*. Pacific Marine Science Report 78-6, Institute of Ocean Sciences, Sidney, B.C., Canada (1978) 57p.
- Levine, M.D., Paulson, C.A. and Morison, J.H. Internal waves in the Arctic Ocean: Comparison with lower-latitude observation. *Journal of Physical Oceanography* 15: 800–809 (1985).

- Levine, D.M., Paulson, C.A. and Morison, J.H. Observations of internal gravity waves under the Arctic pack ice. *Journal of Geophysical Research* 92(C1): 779–782 (1987).
- Levine, D.M., Padman, L., Muench, R.D. and Morison, J.H. Internal waves and tides in the western Weddell Sea: Observations from Ice Station Weddell. *Journal of Geophysical Research* 102(C1): 1073–1089 (1997).
- Merrifield, M.A. and Pinkel, R. Inertial currents in the Beaufort Sea: Observations of response to wind and shear. *Journal of Geophysical Research* 101(C3): 6577–6590 (1996).
- Plueddemann, A.J. Internal wave observations from the Arctic Environmental Drifting Buoy. *Journal of Geophysical Research* 97(C8): 12,619–12,638 (1992).
- Torrence, C. and Compo, G.P. A practical guide to wavelet analysis. *Bulletin of American Meteorological Society* 79: 61–78 (1998).
- Zakharov, V.F. *Sea Ice in the Climate System*, WMO/TD 782. World Meteorological Organization, Geneva (1997) 213p.